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14. ABSTRACT
Significant contributions have been made in the course of this project. These results are published in 14 journal papers and 18 refereed conference papers. The journal papers appeared in prestigious journals such as IEEE/ACM Transactions on Networking, IEEE Transactions on Computers, IEEE Transactions on Wireless Communications, and IEEE Transactions on Vehicular Technology. The Conference papers appeared in IEEE INFOCOM (2005, 2006, 2007, 2008), ACM MobiHoc (2005), IEEE Military Communication Conference (2004, 2006, 2007), IEEE International Conference on Communications (2005, 2006, 2007), and IEEE Global Communications Conference (2005, 2007). In the area of relay node placement, we

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Report Title

Robustness and Survivability Issues in Wireless Ad Hoc Networks

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List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

[J15] Satyajayant Misra, Guoliang Xue, and Sarvesh Bhardwaj;
Secure and robust localization in a wireless ad hoc environment;
IEEE Transactions on Vehicular Technology;
in press.

[J14] Satyajayant Misra, M. Reisslein, and Guoliang Xue;
A survey of multimedia streaming in wireless sensor networks;
IEEE Communications Surveys and Tutorials;
in press.

[J13] Jian Tang, Satyajayant Misra, and Guoliang Xue;
Joint spectrum allocation and scheduling for fair spectrum sharing in cognitive radio wireless networks;
Computer Networks Journal;
in press.

[J12] Jian Tang, Guoliang Xue and Weiyi Zhang;
Cross-Layer optimization for end-to-end rate allocation in multi-radio wireless mesh networks;
ACM Wireless Networks (WINET);
in press.

[J11] Guoliang Xue, Weiyi Zhang, Jian Tang, and K. Thulasiraman;
Polynomial time approximation algorithms for multi-constrained QoS routing;
IEEE/ACM Transactions on Networking;
Vol. 16(2008), pp. 656--669.

[J10] Weiyi Zhang, Guoliang Xue, Jian Tang, and K. Thulasiraman;
Faster algorithms for constructing recovery trees enhancing QoP and QoS;
IEEE/ACM Transactions on Networking;
Vol. 16(2008), pp. pp. 642-655.

[J09] Jian Tang, Guoliang Xue and Weiyi Zhang;
Cross-layer design for end-to-end throughput and fairness enhancement in multi-channel wireless mesh networks;
IEEE Transactions on Wireless Communications;
Vol. 6(2007), pp. 3482--3486.

[J08] Guoliang Xue, Arunabha Sen, Weiyi Zhang, Jian Tang, and Krishnaiyan Thulasiraman;
Finding a path subject to many additive QoS constraints;
IEEE/ACM Transactions on Networking;
Vol. 15(2007), pp. 201--211.

[J07] Guoliang Xue and Kami Makki;
Multi-constrained QoS routing: a norm approach;
IEEE Transactions on Computers;
Vol. 56(2007), pp. 859--863.

[J06] Errol L. Lloyd and Guoliang Xue;
Relay node placement in wireless sensor networks;
IEEE Transactions on Computers;
Vol. 56(2007), pp. 134--138.

[J05] Jian Tang, Guoliang Xue, Christopher Chandler, and Weiyi Zhang;
Link scheduling with power control for throughput enhancement in multihop wireless networks;
IEEE Transactions on Vehicular Technology;
Vol. 55(2006), pp. 733--742.

[J04] Satyajayant Misra and Guoliang Xue;
Efficient anonymity schemes for clustered wireless sensor networks;
International Journal of Sensor Networks;
Vol. 1(2006), pp. 50--63.

[J03] Wenye Wang and Guoliang Xue;
A cost-minimization algorithm for fast location tracking in mobile wireless networks;
Computer Networks Journal;
Vol. 50(2006), pp 2713--2726.

[J02] Jian Tang, Guoliang Xue, and Weiyi Zhang;
Reliable ad hoc routing based on mobility prediction;
Journal of Combinatorial Optimization;
Vol. 11(2006), pp. 71--85.

[J01] Jian Tang, Guoliang Xue and Christopher Chandler;
Interference-aware routing and bandwidth allocation for QoS provisioning in multihop wireless networks;
Wiley Journal of Wireless Communication and Mobile Computing;
Vol. 5(2005), pp. 933--943.

Number of Papers published in peer-reviewed journals: 15.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

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(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

[C19] Satyajayant Misra, Don Hong, Guoliang Xue and Jian Tang;
Constrained relay node placement in wireless sensor networks to meet connectivity and survivability requirements;
IEEE INFOCOM'2008, pp. 281--285.

[C18] Satyajayant Misra and Guoliang Xue;
CluRoL: Clustering based robust localization in wireless sensor networks;
IEEE Milcom'2007.

[C17] Satyajayant Misra, Weiyi Zhang, and Guoliang Xue;
A technique to enhance localization in the presence of NLOS errors;
IEEE Globecom'2007, pp. 1070--1075.

[C16] Guoliang Xue and Weiyi Zhang;
Multiconstrained QoS routing: greedy is good;
IEEE Globecom'2007, pp. 1866--1871.
Best Paper Award.

[C15] Jian Tang, Satyajayant Misra, and Guoliang Xue;
Spectrum allocation and scheduling in dynamic spectrum access wireless networks;
IEEE/ACM QShine'2007.

[C14] Weiyi Zhang, Guoliang Xue, and Satyajayant Misra;
Fault-tolerant relay node placement in wireless sensor networks: problems and algorithms;
IEEE INFOCOM'2007, pp. 1649--1657.

[C13] Satyajayant Misra, Guoliang Xue, and Aviral Shrivastava;
Robust localization in wireless sensor networks through the revocation of malicious anchors;
IEEE ICC'07, pp. 3057--3062.

[C12] Satyajayant Misra, Sarvesh Bhardwaj and Guoliang Xue;
ROSETTA: Robust and secure mobile target tracking in a wireless ad hoc environment;
IEEE Milcom'2006.

[C11] Jian Tang Guoliang Xue, and Weiyi Zhang;
End-to-end rate allocation in multi-radio wireless mesh networks: cross-layer schemes;
QShine'2006, Waterloo, August 07-09, 2006;

[C10] Satyajayant Misra and Guoliang Xue;
SAS: A simple anonymity scheme for clustered wireless sensor networks;
IEEE ICC'2006, pp. 3414--3419.

[C09] Weiyi Zhang, Guoliang Xue, Jian Tang, and K. Thulasiraman;
Linear time construction of redundant trees for recovery schemes enhancing QoP and QoS;
IEEE INFOCOM'2005, pp. 2702--2710.

[C08] Jian Tang, Guoliang Xue, and Weiyi Zhang;
Maximum throughput and fair bandwidth allocation in

multi-channel wireless mesh networks;
IEEE INFOCOM'2006, Barcelona, April 23-29, 2006;

[C07] Jian Tang, Guoliang Xue, Christopher Chandler, and Weiyi Zhang;
Link scheduling with power control for throughput enhancement
in multihop wireless networks;
IEEE QShine'2005, Orlando, August 22-24, 2005;

[C06] Jian Tang, Guoliang Xue, Weiyi Zhang;
Power efficient broadcasting and multicasting in wireless
networks with directional antennas;
IEEE ICC'2005, pp. 1438--1442.

[C05] Jian Tang, Guoliang Xue, Weiyi Zhang;
Interference-aware topology control and QoS routing in
multi-channel wireless mesh networks;
ACM MOBIHOC'2005, pp. 68--77.

[C04] Manvendu Bhardwaj, Satyajayant Misra, and Guoliang Xue;
Topology Control in Wireless Ad Hoc Networks using
β-skeletons;
IEEE HPSR'2005, pp. 371--375.

[C03] Jian Tang, Guoliang Xue, Christopher Chandler, Weiyi Zhang;
Interference-aware routing in multi-hop wireless networks
using directional antennas;
IEEE INFOCOM'2005, pp. 751--760.

[C02] Jian Tang, Guoliang Xue, Weiyi Zhang;
Energy efficient survivable broadcasting and multicasting in
wireless ad hoc networks;
IEEE Milcom'04, pp. 1165--1171.

[C01] Jian Tang, Guoliang Xue, Weiyi Zhang;
Reliable routing in mobile ad hoc networks based on mobility
prediction;
IEEE International Conference on Mobile, Ad-Hoc and Sensor
Systems (MASS2004); pp. 466--474.

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 19

(d) Manuscripts

[S04] Satyajayant Misra, Don Hong, and Guoliang Xue;
Constrained relay node placement in wireless sensor networks: Formulation and Approximations;
submitted to IEEE/ACM Transactions on Networking.

[S03] Satyajayant Misra, Guoliang Xue, and Dejun Yang;
Polynomial time approximations for multi-path routing with bandwidth and delay constraints;
submitted to IEEE INFOCOM'2009.

[S02] Satyajayant Misra, Mayank Verma, Dijiang Huang, Guoliang Xue;
SEAS: A Secure and efficient anonymity scheme for low-cost RFID tags;
submitted to ICC'2009: IEEE International Conference on Communications.

[S01] Dejun Yang, Satyajayant Misra, and Guoliang Xue;
A fully polynomial time approximation scheme for fault-tolerant base station placement in WSNs;
submitted to ICC'2009: IEEE International Conference on Communications.

Number of Manuscripts: 4.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Satyajayant Misra	1.00
FTE Equivalent:	**1.00**
Total Number:	**1**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Guoliang Xue	0.11	No
FTE Equivalent:	**0.11**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	0.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	0.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

NAME	
Afsheen Irani	
Manvendu Bharadwaj	
Total Number:	**2**

Names of personnel receiving PHDs

NAME	
Jian Tang	
Weiyi Zhang	
Tie Wang	
Total Number:	**3**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

1 Forward

This is the final report of the project *Robustness and Survivability Issues in Wireless Ad Hoc Networks*. The PI and his team has successfully completed the research tasks stated in the project. The research resulted in 15 journal publications and 19 refereed conference publications. The journal publications include 3 papers in **IEEE/ACM Transactions on Networking** (which is *the premier journal in networking*), 2 papers in **IEEE Transactions on Computers** (which is the flagship journal of the IEEE Computer Society), and 4 papers in other **IEEE Transactions/Journals**. The conference publications include 5 papers in **IEEE INFOCOM (2005, 2006, 2007, 2008)**, 1 paper in **ACM MobiHoc'2005**, 3 papers in **IEEE Military Communications Conference (2004, 2006, 2007)**, 3 papers in **IEEE ICC (2005, 2006, 2007)**, and 2 papers in **IEEE Globecom'2007**, including a **BEST PAPER AWARD**.

Three students received PhD degrees. Two of them won the **Outstanding PhD Student Award** of the CSE Department at Arizona State University in 2006 and 2007, respectively. They went on to assume tenure-track faculty jobs at Montana State University and North Dakota State University, respectively. The PI won the **Researcher of the Year Award** of the CSE Department at Arizona State University in 2007, and has been appointed as a TPC co-Chair of **IEEE INFOCOM'2010**, the premier IEEE conference in computer communications.

The problems studied are described in Section 2. The most important research results are summarized in Section 3.

2 Statement of the Problems Studied

The objective of the proposed research is to apply techniques from discrete math and theoretical computer science to study robustness and survivability issues in wireless ad hoc networks. This study will be concentrated on three optimization problems that have direct military applications.

The first problem addresses relay node placement in wireless sensor networks. Given a set of sensor nodes in the Euclidean plane, the *connected single cover* relay node placement problem seeks to place a minimum number of more powerful but more expensive relay nodes into the network so that each sensor node can communicate to at least one relay node and the relay nodes themselves form a connected network. The *2-connected double cover* relay node placement problem seeks to place a minimum number of relay nodes so that each sensor node can communicate to at least two relay nodes and the relay nodes themselves form a 2-connected network. These problems are NP-hard in nature. The PI proposes to design efficient approximation algorithms.

The second problem addresses survivable routing in a wireless network. Survivable point-to-point routing in a wireless network is achieved by routing simultaneously on two node-

disjoint paths. Survivable multicast routing in a wireless network is achieved by routing on two *independent* multicast trees. The independent multicast trees do not have to be disjoint. However, multicasting along the two trees together will be resilient to single node failure. The PI proposes to design effective algorithms which take into account both survivability and energy efficiency simultaneously.

The third problem addresses robust routing in mobile ad hoc networks using mobility predictions. To establish a wireless path connecting a source node and a destination node in a mobile ad hoc network, one needs to find a sequence of wireless links connecting the source to the destination. However, a wireless link may fail shortly after the establishment of the path due to mobility of the mobile nodes. The PI will study a quality of service (QoS) version of this routing problem and design efficient algorithms for computing a path with guaranteed path lifetime. This is achieved by modeling the working area using a waypoint graph and precomputing a link duration table using dynamic programming. Survivability issues are also investigated.

3 Summary of the Most Important Results

The PI and his team have made some significant discoveries and contributions in the proposed studies. They have also made significant discoveries in areas that are related to the proposed studied. The following are some highlights of the research findings.

3.1 Relay Node Placement in Wireless Sensor Networks

Background

A wireless sensor network (WSN) consists of many low-cost and low-power *sensor nodes* (SNs). Since these sensor nodes are usually deployed in harsh environment, network lifetime and survivability are important issues. Since energy consumption is proportional to d^κ for transmitting over distance d, where κ is a constant in the interval $[2,4]$, long distance transmission in WSNs is costly. To prolong network lifetime while meeting certain network specifications, researchers have proposed to deploy in a WSN a small number of costly, but more powerful *relay nodes* (RNs) whose main function is to communicate with the SNs and other RNs.

History

In a 1999 paper published in the journal Information Processing Letters [5], Guoliang Xue (then an Associate Professor of Computer Science at the University of Vermont) and his postdoc Guohui Lin defined the *Steiner minimum tree with minimum number of Steiner points and bounded edge length* problem (SMT-MSPBEL). At that time, they were interested in placing the minimum number of amplifiers in a wide area optical network. Due to the loss of signal strength in optical fibers, there is a bound on the distance that the optical signals are allowed to travel without amplifiers. Lin and Xue proved that the problem is

actually NP-hard, meaning that it is unlikely to have a polynomial time algorithm that solves this problem optimally. At the same time, they proposed a very simple algorithm that can compute a close to optimal solution in polynomial time. Their algorithm is simple: compute an Euclidean minimum spanning tree connecting the network nodes, then deploy the minimum number of amplifiers along each edge of the minimum spanning tree. They showed that the number of amplifiers required by their simple scheme is no more than 5 times the number of amplifiers required in an optimal solution. Later, together with other researchers, they further proved that the number of amplifiers required by their simple scheme is no more than 4 times the number of amplifiers required in an optimal solution. They also designed a more sophisticated algorithm which reduced the performance ratio from 4 to 3. Four years later, researchers have discovered that this problem can be used to model the relay node placement problem in wireless sensor networks, by simply changing amplifiers in optical networks to relay nodes in wireless sensor networks. Till that time, the relay node placement problem considers deploying a minimum number of relay nodes in a wireless sensor network so that between every pair of sensor nodes, there is a path consisting of relay nodes and/or sensor nodes where each hop of the path is no longer than the common transmission range $r > 0$ of the sensor nodes.

In a paper published in the proceedings of the *2004 IEEE Workshop on High Performance Switching and Routing* [3], Guoliang Xue (then an Associate Professor of Computer Science and Engineering at Arizona State University) and two graduate students at ASU further refined the relay node placement problem to the case where the hop between two relay nodes is only required to be bounded by the common communication range $R \geq r$ or the relay nodes. They further defined the single-tiered relay node placement problem (where both relay nodes and sensor nodes can forward packets) and the two-tiered relay node placement problem (where the sensor nodes only transmit the sensed information, but do not forward other packets). In addition, they defined the fault-tolerant relay node placement problems where the network remain connected with the failure of a sensor node or a relay node.

This problem has been been studied by many researchers, including those from MIT [1, 11], UMD [4], and University of Delaware [2]. Research papers are published in places including IEEE Transactions on Computers, IEEE INFOCOM, ACM MobiHoc, IEEE International Conference on Communications, IEEE High Performance Switching and Routing, and Computer Communications. Almost all of the algorithms follow the minimum spanning tree based approach proposed by Lin and Xue in their 1999 paper.

Figure 1 illustrates the single-tiered relay node placement problem. Here we have a sensor network where the sensor nodes are already deployed with known locations. The goal is to deploy a minimum number of relay nodes so that between every sensor node and a base station, there is a path consisting of sensor and/or relay nodes where two consecutive nodes along the path are within transmission range of each other. In the fault-tolerant version of this problem, we require that between every sensor node and a base station, there exists a pair of node disjoint paths.

Figure 2 illustrates the two-tiered relay node placement problem. Here we have a sensor

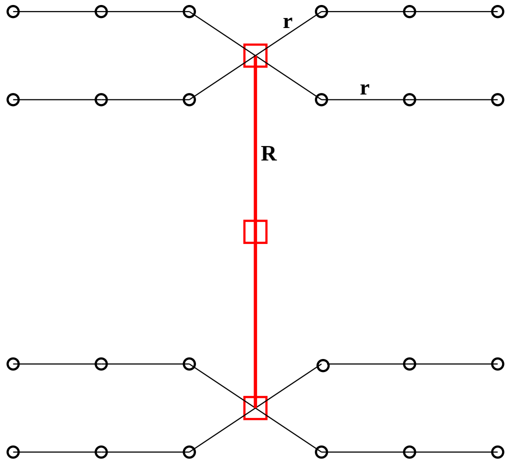
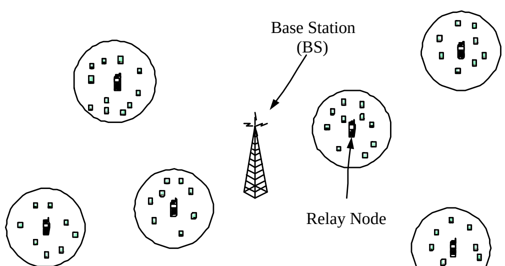
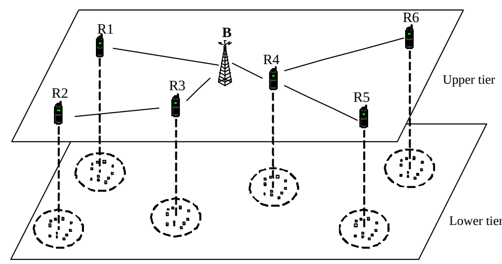


Figure 1: Single-tiered relay node placement: small circles represent sensor nodes, while the big squares represent relay nodes.



(a) Physical view



(b) Hierarchical view

Figure 2: Two-tiered relay node placement: sensor nodes only send the sensed information to the near-by relay node, but do not forward other packets.

network where the sensor nodes are already deployed with known locations. The goal is to deploy a minimum number of relay nodes so that between every sensor node and a base station, there is a connecting path whose internal nodes are all relay nodes and that two consecutive nodes along the path are within transmission of each other. In the fault-tolerant version of this problem, we require that between every sensor node and a base station, there exists a pair of node disjoint paths.

Major Contributions:

We have three significant publications in this area, getting the results exceeding the expectations specified in the proposal. In the first paper [6], we consider both the single-tiered and the two-tiered relay node placement problems, which only ensure connectivity (not fault-tolerant). This is the first paper which deals with these problems where relay nodes can have bigger transmission range than the sensor nodes and that there is no restriction on

sensor nodes distribution. For the single-tiered problem, we present an algorithm that find a feasible relay node placement which uses no more than 7 times the number of relay nodes than required by an optimal solution. For the two-tiered problem, we present an algorithm that find a feasible relay node placement which uses no more than $(5+\epsilon)$ times the number of relay nodes than required by an optimal solution, where $\epsilon > 0$ is any given positive constant.

In the second paper [21], we study fault-tolerant versions of this problem, where we want to deploy a minimum number of relay nodes so that between any sensor node and a base station there are two node-disjoint paths. For both the single-tiered version and the two-tiered version of the problem, we present polynomial time approximation algorithms which provide a solution where the number of relay nodes used is bounded by a small constant times the number of relay nodes used in an optimal solution. The results in these papers improve the current state of the art significantly.

In the third paper [8], we study constrained versions of this problem, where the relay nodes can only be placed in a set of candidate locations. This paper deals with the physical constraints that previous studies have not considered. Again, we have designed polynomial time approximation algorithms with small constant approximation ratios.

3.2 Survivable Routing in Networks

We have also completed the research tasks on the second and third problems. In papers [19, 20], we have presented very fast algorithms for constructing a pair of redundant trees that can be used for survivable unicast and multicast. The technique is used in [12] to design energy efficient survivable broadcast and multicast in wireless ad hoc networks. This technique has been used by other researchers in the design of routing tables for wireless sensor networks [14]. In [13], we have designed a reliable ad hoc routing protocol based on mobility predictions. This is the first work to provide guaranteed connectivity in mobile ad hoc networks.

3.3 Robust Sensor Localization and Target Tracking

Robust sensor localization and target tracking are challenging problems that are useful in military applications. These tasks are even more challenging in the presence of measurement error and/or malicious anchor nodes. We have two major contributions in this area:

In the first paper [7], we study the problem of accurate tracking of a mobile target by a central authority, using distance estimates obtained by a group of untrusted anchors within the communication range of the target. Given the untrusted environment of wireless ad hoc networks, we show how to perform accurate localization of the target in the presence of some compromised and colluding malicious anchors that lie about the position of the target. We also show how to identify most of these malicious anchors. In the case where measurements are error-free, we derive an upper bound (B) on the number of malicious anchors that may be involved in localizing the target while still not being able to undermine its accurate localization. We propose a scheme that correctly localizes the target, given that

the number of malicious anchors within its range is no more than B. It also identifies all the malicious anchors. In the presence of positive measurement errors, we propose a scheme that can localize the target despite the presence of an arbitrary number of malicious anchors in its range. When the number of malicious anchors are no more than B, our scheme localizes the target with an error less than 1m and is also able to identify more than 80% of the malicious anchors. Both our schemes are simple and easy to implement. The extended version of this paper has been accepted for publication in IEEE Transactions on Vehicular Technology [9].

In the second paper [10], we study localization of a sensor node through the use of anchor nodes where some of the anchor nodes may be malicious. We propose an efficient scheme that helps identify and revoke these malicious anchors. We use a mobile verifier (MV) that moves throughout the network, in some pre-determined manner, and obtains multiple location references from each anchor. For each anchor, the MV tests the mean and the variance of the collected sample to identify if the anchor is malicious. We show through simulations that our scheme successfully identifies more than 80% of malicious anchors with less than 60 references from each. Also, the percentage of false positives is close to 0.

3.4 Multi-Constrained Quality of Service Routing

A fundamental problem in quality-of-service (QoS) routing is the multi-constrained path problem, where one seeks a source-destination path satisfying $K \geq 2$ additive QoS constraints in a network with K additive QoS parameters. For example, each link in the network may have a cost and a delay. Then a path in the network would also have a cost and a delay, where the cost of the path is the sum of the edge costs over all edges on the path, and the delay of the path is the sum of the edge delays over all edges on the path. A typical problem is to ask for a path connecting a pair of nodes such that the path cost is no more than a specified cost constraint and the path delay is no more than a specified delay constraint. This problem is NP-hard, but has many important applications. We have made a sequence of significant contributions in this area:

In the first paper [16], we study the problem with $K \geq 2$ additive QoS constraints. We present a simple K-approximation algorithm based on the weighted infinity norm of the K edge weights. We also present a fully polynomial time approximation scheme for this problem.

In the second paper [15], we generalize the K-approximation algorithm proposed in the first paper to a large class of K-approximation algorithms, providing the theoretical support of many previously known heuristic algorithms.

In the third paper [18], we improve the long-standing best-known algorithm for the Delay Constrained Least Cost path problem, and present improved approximation algorithms for another well-known algorithm. This paper advances our knowledge in this area.

In a fourth paper [17], we presented a greedy algorithm that is as simple as the Dijkstra's algorithm for computing a shortest path, and proved that the computed path is within a small constant from the optimal solution. This paper received a **BEST PAPER AWARD**

at IEEE Globecom'2007. Though not specified in the proposal, the problems studied in this section are related to the proposal and have important military applications.

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[6] E. Lloyd and G. Xue; Relay node placement in wireless sensor networks; **IEEE Transactions on Computers**; Vol. 56(2007), pp. 859–863.

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